ECE 371
Materials and Devices

11/7/19 - Lecture 20

Space Charge Width, Reverse Bias, Capacitance

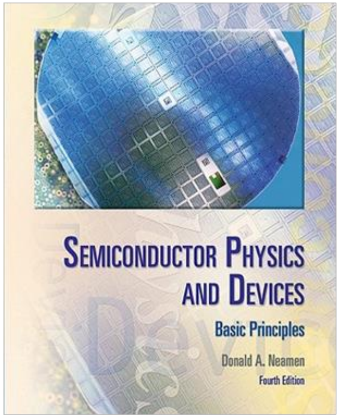
General Information

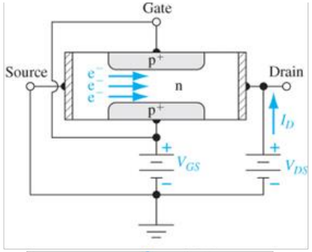
- Homework 6 due today before class
- Homework 7 assigned and due Thursday 11/21
- I will post solutions to midterm 2 later today
- If there are midterm grading questions, please follow this process:
  1. Review my solutions to compare your response to what I was looking for.
  2. If reviewing the solutions does not resolve your grading question, please see Hasan.
  3. If grading questions still cannot be resolved with Hasan, please see me.
- Reading for next time: 7.3, 7.4, 8.1

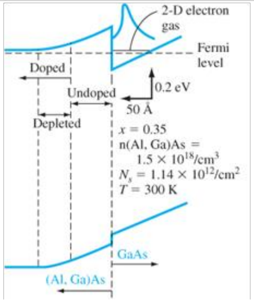
Spring 2020: ECE 471 – Materials and Devices II

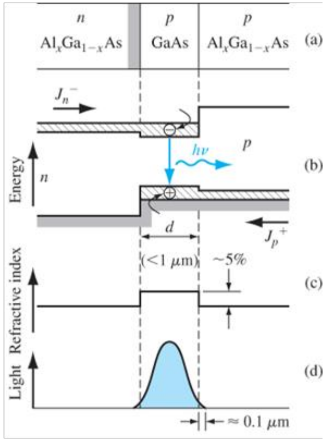
Location and Time: EECE-218, Tu-Th 9:30 – 10:45 am

Prerequisites: ECE 371 (or permission of instructor)





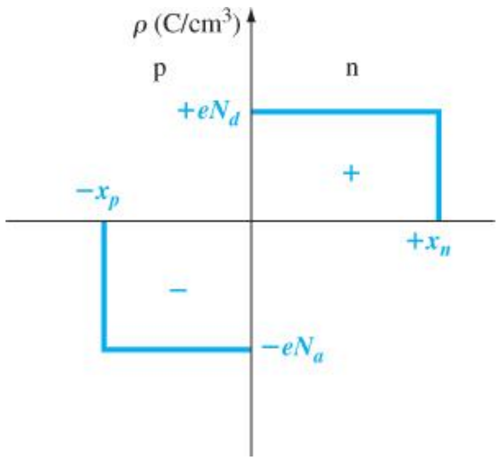




UNM Catalog Description:
An intermediate study of semiconductor materials, energy band structure, p-n junctions, ideal and non-ideal effects in field effect and bipolar transistors.

Content Details:
The course will cover portions of chapters 6, 9, and 10-14 from *Semiconductor Physics and Devices* by Donald Neamen. Some of the covered topics will include: carrier generation and recombination, carrier lifetime, ambipolar transport, quasi-Fermi levels, traps, non-ideal effects, junction breakdown, diffusion capacitance, Schottky barrier diodes, ohmic contacts, heterostructures, device physics of MOSFETs, BJTs, HEMTs, and JFETs, tunnel diodes, small-signal equivalent circuits, brief introduction to optical materials and devices (solar cells, photodetectors, LEDs, lasers).

Space Charge Width



- Depletion splits between the n and p sides and the splitting ratio depends upon the doping
- For an asymmetric junction, most of the space charge width occurs on the lightly doped side
- Total charge on each side must be equal ($N_a x_p = N_d x_n$)

space charge width on n side

$$x_n = \left[\frac{2\varepsilon_s V_{bi}}{e}\left(\frac{N_a}{N_d}\right)\frac{1}{N_a + N_d}\right]^{\frac{1}{2}}$$

space charge width on p side

$$x_p = \left[\frac{2\varepsilon_s V_{bi}}{e}\left(\frac{N_d}{N_a}\right)\frac{1}{N_a + N_d}\right]^{\frac{1}{2}}$$

total space charge width

$$W = x_n + x_p = \left[\frac{2\varepsilon_s V_{bi}}{e}\frac{N_a + N_d}{N_a N_d}\right]^{\frac{1}{2}}$$

Test Your Understanding 7.1

TYU 7.1 Calculate V_{bi}, x_n, x_p, W, and $|\mathrm{E}_{\max}|$ for a silicon pn junction at zero bias and $T = 300$ K for doping concentrations of (*a*) $N_a = 2 \times 10^{17}\ \mathrm{cm}^{-3}$, $N_d = 10^{16}\ \mathrm{cm}^{-3}$ and (*b*) $N_a = 4 \times 10^{15}\ \mathrm{cm}^{-3}$, $N_d = 3 \times 10^{16}\ \mathrm{cm}^{-3}$.

[Ans. (*a*) $V_{bi} = 0.772$ V, $x_n = 0.3085\ \mu$m, $x_p = 0.0154\ \mu$m, $W = 0.3240\ \mu$m, $|\mathrm{E}_{\max}| = 4.77 \times 10^4$ V/cm; (*b*) $V_{bi} = 0.699$ V, $x_n = 0.0596\ \mu$m, $x_p = 0.4469\ \mu$m, $W = 0.5064\ \mu$m, $|\mathrm{E}_{\max}| = 2.76 \times 10^4$ V/cm]

Reverse Bias

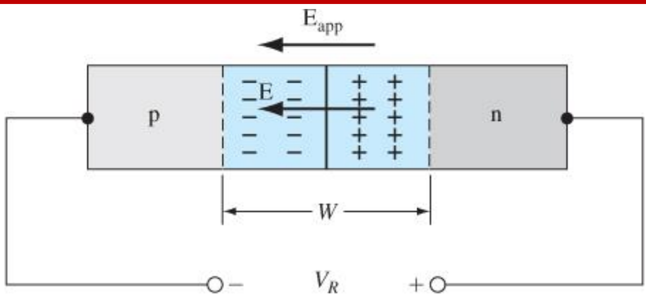


Figure 7.8 | A pn junction, with an applied reverse-biased voltage, showing the directions of the electric field induced by V_R and the space charge electric field.

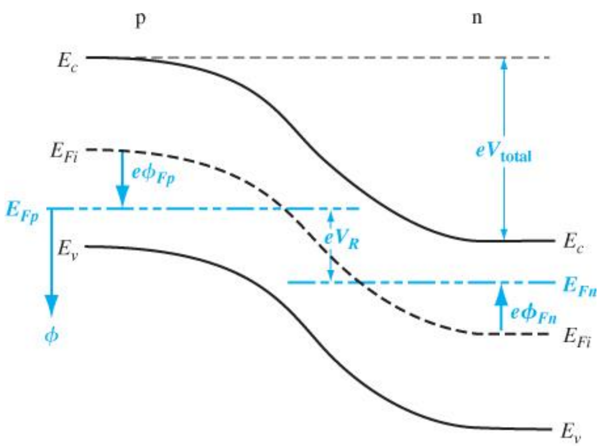


Figure 7.7 | Energy-band diagram of a pn junction under reverse bias.

- Apply + potential to n-side relative to p-side
- Potential on n-side is raised relative to p-side
- $V_{total} = V_{bi} + V_R$ reverse bias (will be positive)
- Assume applied voltage (V_R) is entirely dropped across the depletion region
- E-field in depletion region increases
- Depletion width (W) also increases
- Non-thermal-equilibrium$\Rightarrow$ Fermi level not constant anymore
- E_{Fn} and E_{Fp} are "quasi-Fermi levels"

Reverse Bias Equations

- In all previous equations containing V_{bi}, we can simply replace V_{bi} with $V_{bi} + V_R$
- This is justified since the analysis of E(x) and ϕ(x) are still the same, only with larger x_n and x_p now

depletion width has increased

$$E(x) = \frac{-eN_a}{\varepsilon_s}(x + x_p) \text{ for } -x_p \le x \le 0$$

$$E(x) = \frac{-eN_d}{\varepsilon_s}(x_n - x) \text{ for } 0 \le x \le x_n$$

$$x_n = \left[\frac{2\varepsilon_s(V_{bi}+V_R)}{e}\left(\frac{N_a}{N_d}\right)\frac{1}{N_a + N_d}\right]^{\frac{1}{2}}$$

$$x_p = \left[\frac{2\varepsilon_s(V_{bi}+V_R)}{e}\left(\frac{N_d}{N_a}\right)\frac{1}{N_a + N_d}\right]^{\frac{1}{2}}$$

$$W = x_n + x_p = \left[\frac{2\varepsilon_s(V_{bi}+V_R)}{e}\frac{N_a + N_d}{N_a N_d}\right]^{\frac{1}{2}}$$

$$E_{max} = -\left[\frac{2e(V_{bi}+V_R)}{\varepsilon_s}\frac{N_a N_d}{N_a + N_d}\right]^{\frac{1}{2}}$$

$$E_{max} = \frac{-2(V_{bi} + V_R)}{W}$$

Depletion ~~Junction~~ Capacitance

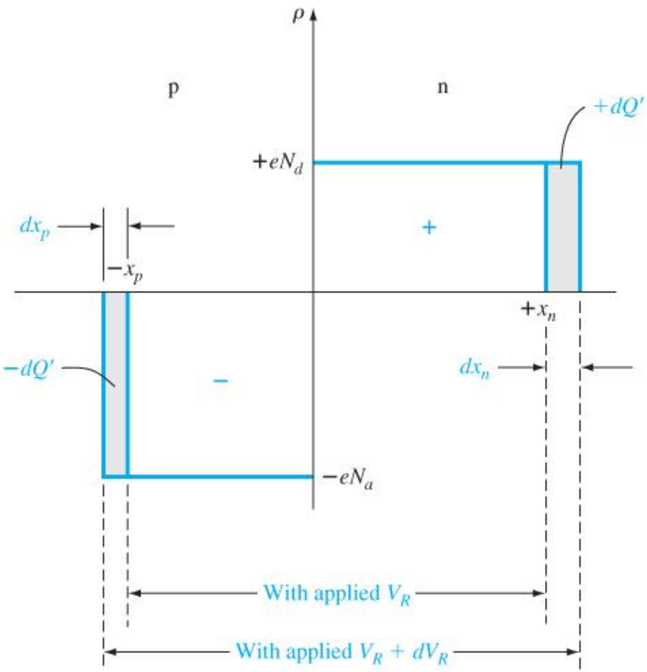


Figure 7.9 | Differential change in the space charge width with a differential change in reverse-biased voltage for a uniformly doped pn junction.

reverse bias increases
capacitance decreases

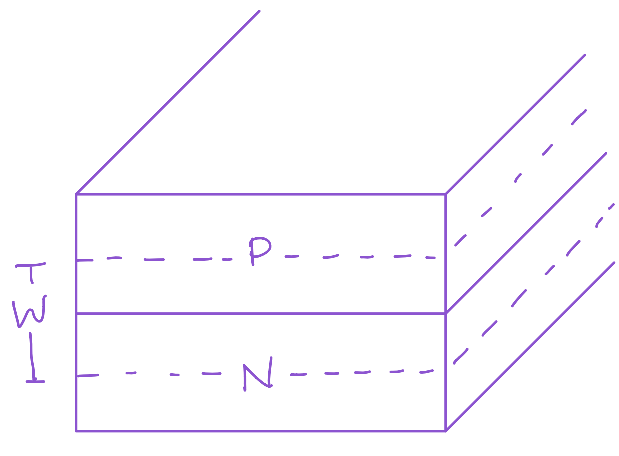
- Separation of + and – charges ⇒ junction capacitance
- Similar to parallel plate capacitor
- Increasing reverse bias by dV_R uncovers additional charges

$$\boxed{C' = \frac{dQ'}{dV_R} = \left[\frac{e\varepsilon_s N_a N_d}{2(V_{bi} + V_R)(N_a + N_d)}\right]^{\frac{1}{2}}} = \frac{\varepsilon_s A}{W}$$

*Depletion layer capacitance per unit area, units are [F/cm^2]

- If the cross-sectional area of the junction is known, the true capacitance is

$$\boxed{C = C' * A}$$



P
N
W

CV Measurement on One-Sided Junction

- A one-sided junction can be used to determine the built-in voltage and doping concentration
- Imagine a one-sided junction with $N_a \gg N_d$ and $W \approx x_n$
- Plot $\left(\frac{1}{C'}\right)^2$ vs V_R

$$\boxed{C' \approx \left[\frac{e\varepsilon_s N_d}{2(V_{bi} + V_R)}\right]^{\frac{1}{2}}}$$

only dependent on low doped side

$$\left(\frac{1}{C'}\right)^2 = \frac{2(V_{bi} + V_R)}{e\epsilon_s N_d}$$

$$= \underbrace{\frac{2}{\epsilon\epsilon_s N_d}}_{\text{slope}} V_R + \underbrace{\frac{2}{e\epsilon_s N_d} V_{bi}}_{\text{intercept}}$$

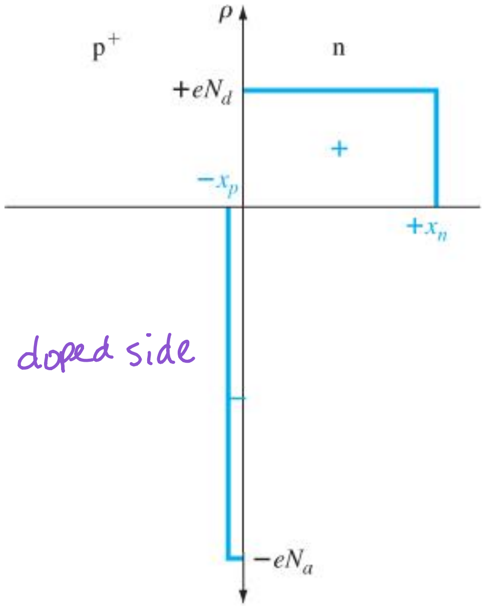


Figure 7.10 | Space charge density of a one-sided p⁻n junction.

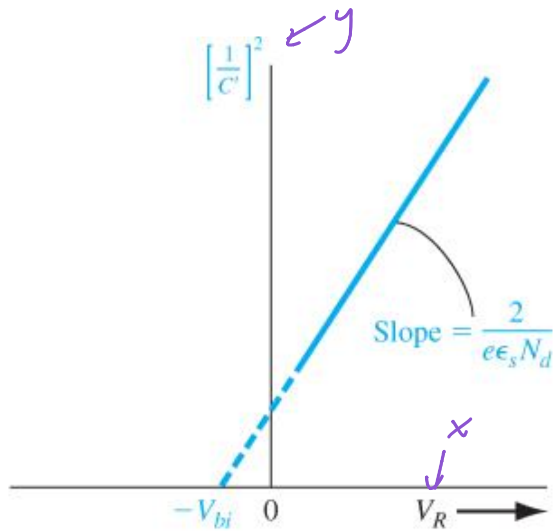


Figure 7.11 | $(1/C')^2$ versus V_R of a uniformly doped pn junction.

know Nd & slope from graph, can find V_R intercept and can get V_{bi} from

Biased pn Junctions

- No current due to potential barrier
- E is all built in to junction

- Potential barrier increases
- Still no current
- E increases
- Fermi levels separate

- Potential barrier decreases
- E decreases
- Electrons and holes diffuse across junction
- Current flows

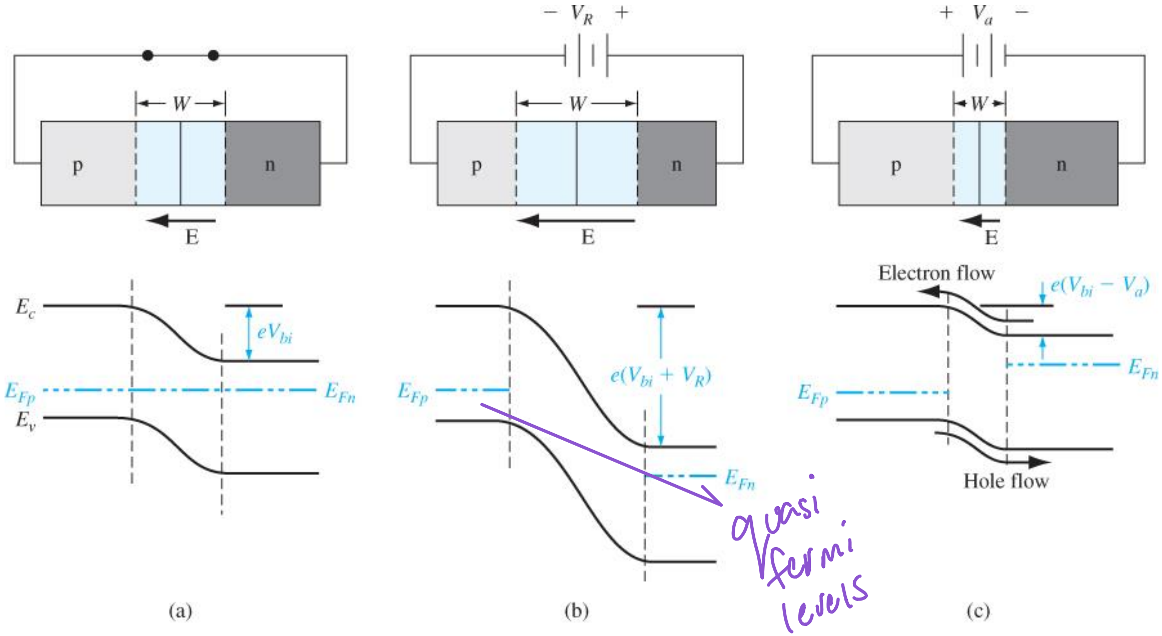


Figure 8.1 | A pn junction and its associated energy-band diagram for (a) zero bias, (b) reverse bias, and (c) forward bias.